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Regional and global hydrology and water resources issues: The role of international and national programs

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Abstract. This paper presents an overview of water resources issues in the context of world population growth, climate change, and variability, and provides examples of how these issues affect local and regional water policy concerns. Also discussed is the associated research of the international scientific community in regard to physically-based modeling of the hydrological cycle, with special focus on the Global Energy and Water cycle EXperiment (GEWEX) Programme. The critical role of precipitation measurements for climate model accuracy is emphasized, with a review of several satellite methods and strategies for improving precipitation measurements. Finally, the impact of semiarid regions on global hydrologic issues is underscored with a review of research conducted by SAHRA, the National Science Foundation Science and Technology Center dedicated to Sustainability of semi-Arid Hydrology and Riparian Areas.

Key words. Climate change; climate variability; GEWEX; precipitation; SAHRA; water cycle; water resources.

Introduction

When one reviews a few basic facts about the Earth's water resources, it becomes evident that water quality and quantity will present daunting challenges for scientists and water policy experts in the 21st Century. For example, the two primary sources of fresh water used for human consumption are groundwater and surface water, yet the amount of fresh water on Earth is very limited. Only approximately 1.69% of the Earth's total water is groundwater, and only 0.014% is attributed to rivers, lakes, and streams (Maidment, 1993). Of the remaining water, most is saline and thus not potable (oceanic), while some is arrested in ice caps and glaciers, and a very small amount exists as soil and atmospheric moisture.

Combined with the fact of limited fresh water resources is the compounding issue of Earth's human population growth. The population of the Earth is expected to grow to about 8.3 billion by year 2025 from the most recent estimate of 5.7 billion in 1995 (U.S. Bureau of the Census, 1999). Because some countries – many in the developing world – are expected to have the highest increase in population, they will face incredible challenges of how to meet future water needs. Clearly, this may pose problems in the near future, as there are numerous competing demands for fresh water use today, the most notable of which include: domestic uses, power and industry, agriculture, navigation, recreation, and wildlife.

Several examples offer insight into the challenges of sustainable water resources use and allocation. Figure 1 is an example of the water resources situation on the Colorado River basin in the southwest United States. The Colorado River is a primary source of water for a number of Southwestern states, including California, Arizona, New Mexico, Nevada, Utah, Colorado, and Wyoming. The figure shows that, with the construction of the Glen Canyon Dam in 1960, all of the water resources of this river basin became fully allocated by the time the river – what little

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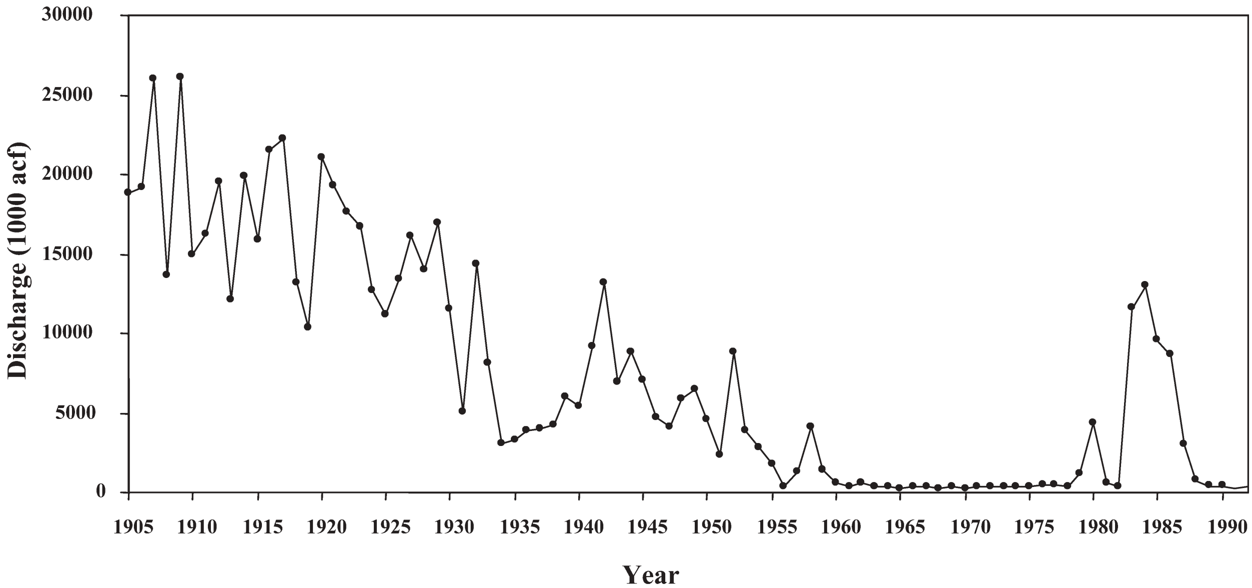

Figure 1. Colorado River flow below all major dams and diversions.

was left – reached the US-Mexico border near the city of Yuma, Arizona (Fig. 1). The 1995 U.S. census puts the population of these southwestern states at 45 million, and it is projected to reach 64 million by the year 2025 (U.S. Bureau of the Census, 2002). As previously stated, we may be facing a very unsustainable situation with respect to the future availability of water, for all its intended purposes, to meet the needs of the added population.

Further complicating the situation is the issue of water quality. The headwaters of the Colorado River are of good quality, where the total dissolved solids (TDS) are about 50 parts per million (WRRC, 1999). By the time the flow reaches the border of Arizona and Mexico, the TDS concentration has increased to 800 parts per million, primarily a result of the return flow from irrigated fields, as well as from natural causes. (Current US Environmental Protection Agency drinking water standards suggest TDS should not exceed 500 ppm (USEPA, 2002)).

The example is not unique to the Colorado River basin. Many river basins in the world are experiencing similar conditions. The Colorado River provides an example of anthropogenically caused water-quality deterioration. The case of the Murray River in Australia illustrates that gradual, naturally-occurring clearing of vegetation over the years has resulted in an increase of the river's salinity, which is potentially an irreversible situation (Fig. 2). The reduction in vegetation has also resulted in increased infiltration of water (because of rain) and, thus, has increased the amount of salt drainage through the soil column into the aquifer.

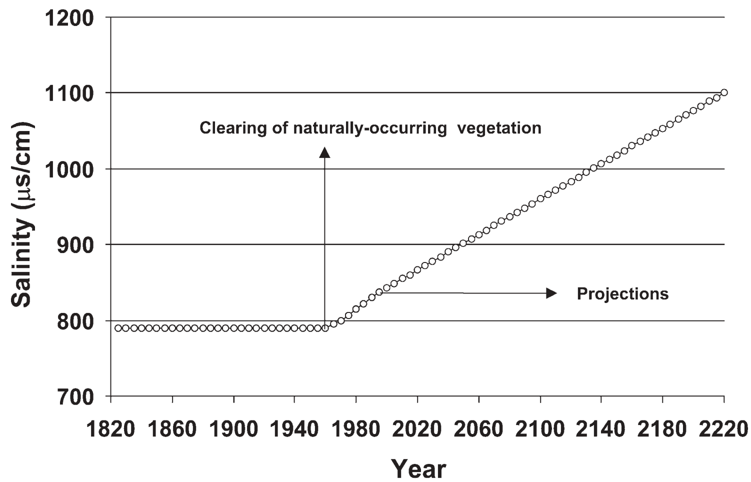

Figure 2. The Murray River, Australia. A salinity increase was caused by naturally occurring clearing of vegetation.

In addition to water quality and quantity problems, depletion of groundwater resources can also cause land subsidence. With the widespread invention and subsequent use of electrical and/or mechanical pumps over the past 100 years, the rate of groundwater resource utilization has become unprecedented in many regions of the world. Because this utilization has far exceeded the natural recharge process of aquifers, many areas are experiencing land subsidence and, hence, a major loss of aquifer storage capacity, which can never be replenished.

Several noteworthy examples include the greater area of the City of Beijing, China, which has seen a decline in its water table by as much as 30 m since 1959. Likewise, the City of Tucson, Arizona, USA – which, until very recently relied exclusively on groundwater for its water supply – has experienced an average decline in the entire basin of approximately 50 m since the 1950s, when the city's population began to increase rapidly (WRRC, 1999). Recently, Tucson's water resources have been supplemented by surface water from the Colorado River, a portion of which is diverted and flows several hundred miles via canal from the north on part of the state. Acquisition and use of this water has allowed Tucson's water managers to decrease groundwater pumping for the first time in decades. Tucson's groundwater table has begun to rise. Unfortunately for many owners of Tucson real estate, the damage from land subsidence cannot be reversed.

The problem of subsidence is widespread; land subsidence from pumping in the San Joaquin Valley, California (USA), and Eloy, Arizona (USA) is causing structural problems while dramatic sinkholes as the result of pumping for irrigation exist in many places in the Middle East. These dramatic differences in subsidence are caused by differences in the geologic media; the loss of an aquifer's storage capacity is dependent upon the original porosity of the aquifer. In general, those aquifers with greater initial porosities will experience more dramatic subsidence than aquifers with lesser porosity. In particular, subsidence and the development of sinkholes may be especially pronounced in aquifers with substantial clay content. In all cases of subsidence, an aquifer's storage capacity is permanently diminished.

Impact of population growth, climate change, and variability on water resources

There is no question that, as the Earth's population grows, the demand for safe, potable water increases. However, the amount of available fresh water worldwide does not change; in many regions, especially those that are arid and semiarid, the mining of fresh water is an unsustainable practice. It is evident from various examples of over-allocation of river waters, decreasing water quality, groundwater declines, land subsidence, and even sinkholes caused by over-pumping, that widespread, current water policies require reconsideration by water resource managers.

Consider the graphic in Figure 3, which shows the distribution of fresh water use in several countries. In many of the figure's examples, a large percentage of a

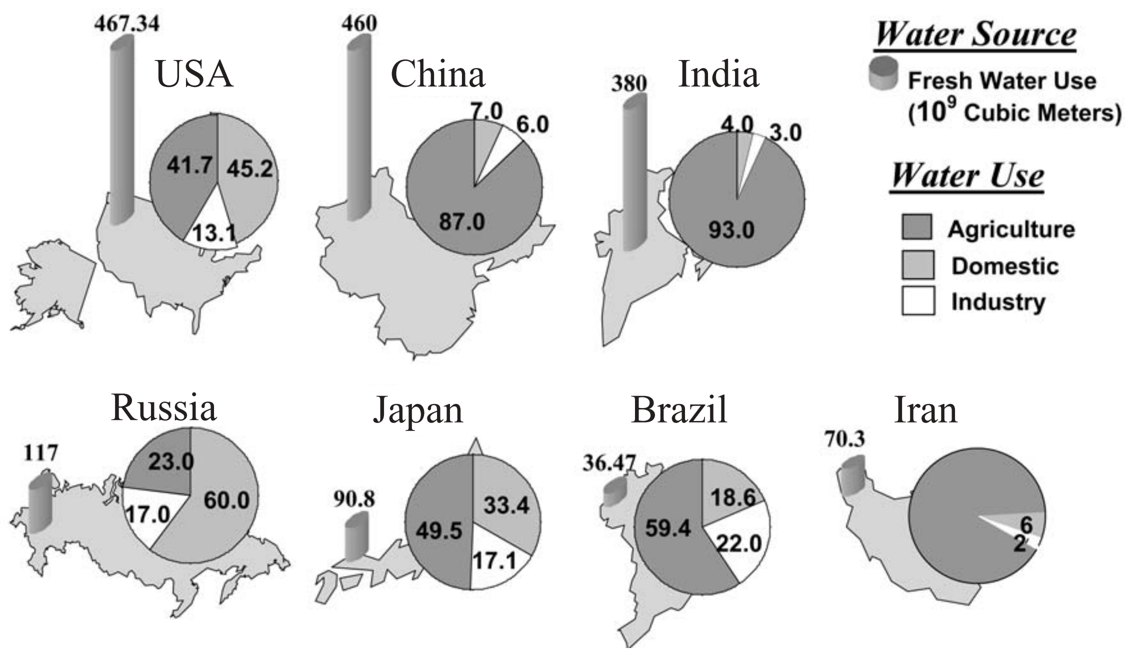

Figure 3. Distribution of freash water use. Note the large percentage of irrigation use in many countries.

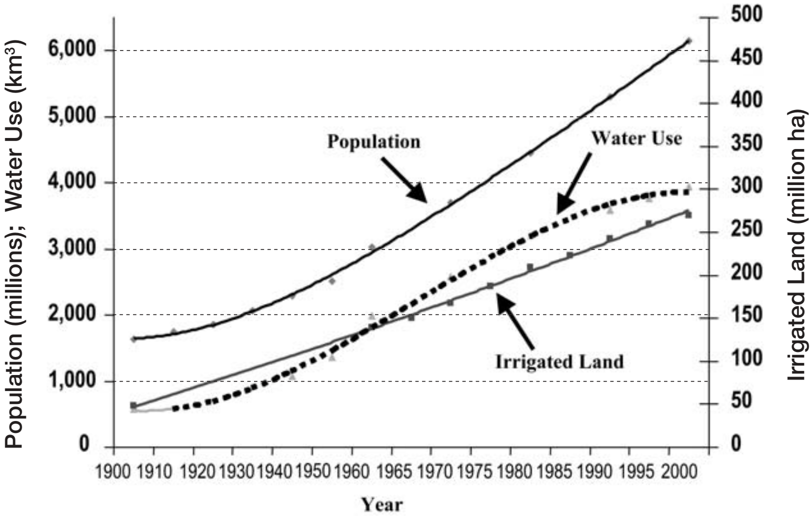

Figure 4. Water use has begun to level off in the past 25 years, despite ongoing increases in population and irrigated acreage. Figure adapted from P. H. Gleick, 1998. The World's Water 1998 – 1999 (Island Press, Washington, D.C.).

country's fresh water is used for irrigation. If water resource managers aim to plan for a sustainable water supply for ever-growing populations, it is clear that a water allocation balance must be struck between urban users and agricultural users who grow the food that feeds the urban populations.

For example, the use of irrigation water for agricultural purposes has increased greatly in efficiency in most developed countries throughout the world. While it is important to consider whether some of the technology that has contributed to this efficiency can be used elsewhere, it is even more critical to focus on policies and politics contributing to water allocation. In particular, urban water users – both domestic and industrial – usually receive the most encouragement to conserve water, but they use far less than is used in the agricultural sectors. In fact, although the world's population increase was roughly parallel with the increase in water use over the past century, the past quarter century has shown a leveling off of water use, despite a continuation in population growth (see Fig. 4). The population increase and leveling off of water use may be explained in part by improvements in water conservation technology, but technological improvements are not likely to sustain an ever-growing population. Eventually, irrigated lands may need to be retired so that the water can be allocated for domestic and industrial uses.

While the direct relation between population growth and increase in water demand is relatively straightforward, the impact of climate change and variability is less well defined. Moreover, different regions will be affected differently by climate changes, and the hydrologic cycle may be intensifying as a result of climate change. While we may anticipate an increase in global average precipitation caused by global warming, not all regions will necessarily see such an increase. Therefore, from a water resources management point of view, the uncertainty associated with regional shifts in precipitation, runoff, etc. will create great challenges for decision-makers and operators of water resources systems. Figure 5 attempts to show spatial and temporal requirements for weather and climate data for different water resources management purposes. This ranges from short-term, hourly forecasts of flash floods, to decade and century scales for groundwater management design and construction of major water resource facilities (e.g., dams, aqueducts, etc.).

To demonstrate the fact that long-term and short-term predictions are integral to each other, an end-to-end approach is necessary to make the transition from seasonal/inter-annual climate predictions to an actual specific storm event, to its impact on water resources and related operational and policy decisions. In the context of the southwest US for example, it is statistically demonstrated that winter precipitation increases during an El Niño year. In fact, during the strong El Niño event of 1997, the southwest US saw a 55 percent increase in precipitation (WRRC, 1999). Among the specific cases was Hurricane Nora in September 1997 (see Fig. 6). The short-term predictions even 24 hours prior to the arrival of the storm predicted the path of the hurricane moving between Tucson and Phoenix, toward the eastern portion of the White Mountains of Arizona. The predicted precipitation amount was approximately four to five inches in a 24-hour period, which would have had a profound impact on the management of the Salt River's reservoir system for the Phoenix metropolitan area (NCEP, 2002). However, the hurricane's actual path deviated 200 miles to the west of its predicted path, with only a trace of rainfall in the Salt River watershed. The

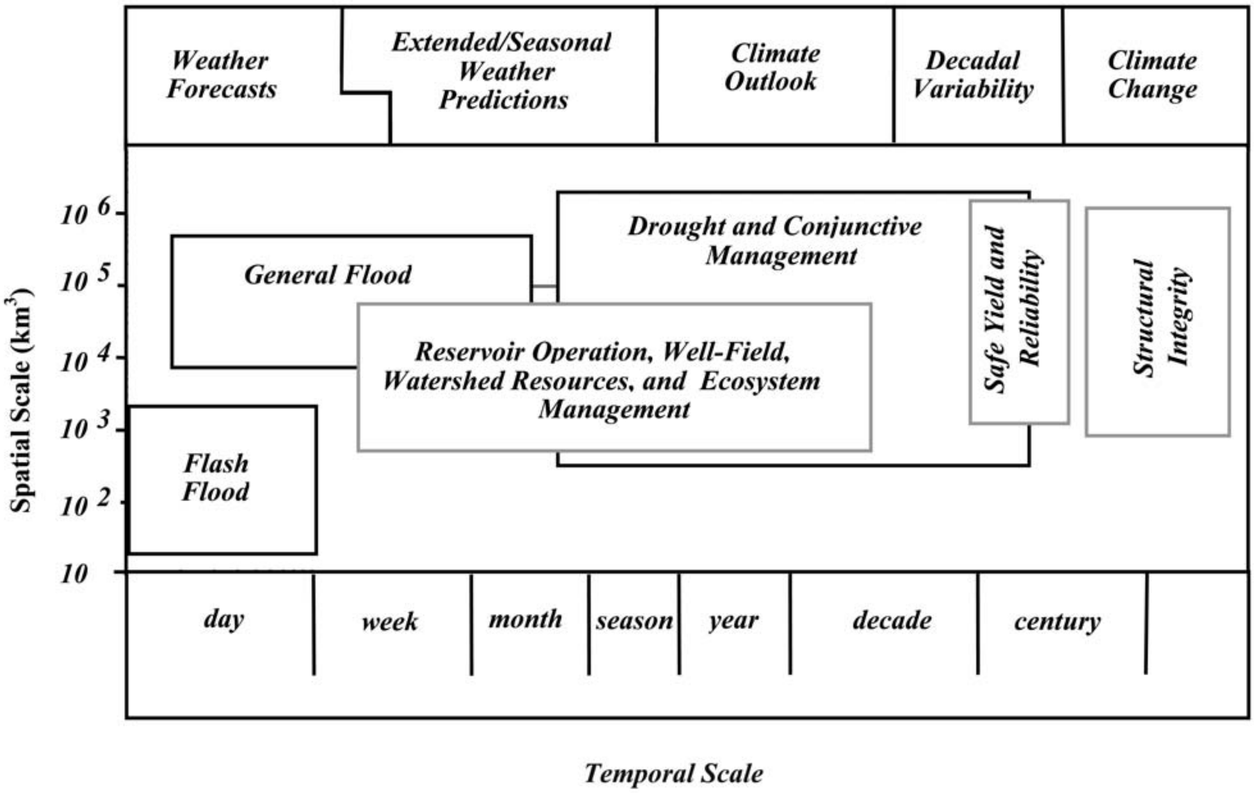

Figure 5. Water resources issues vary in both space and time.

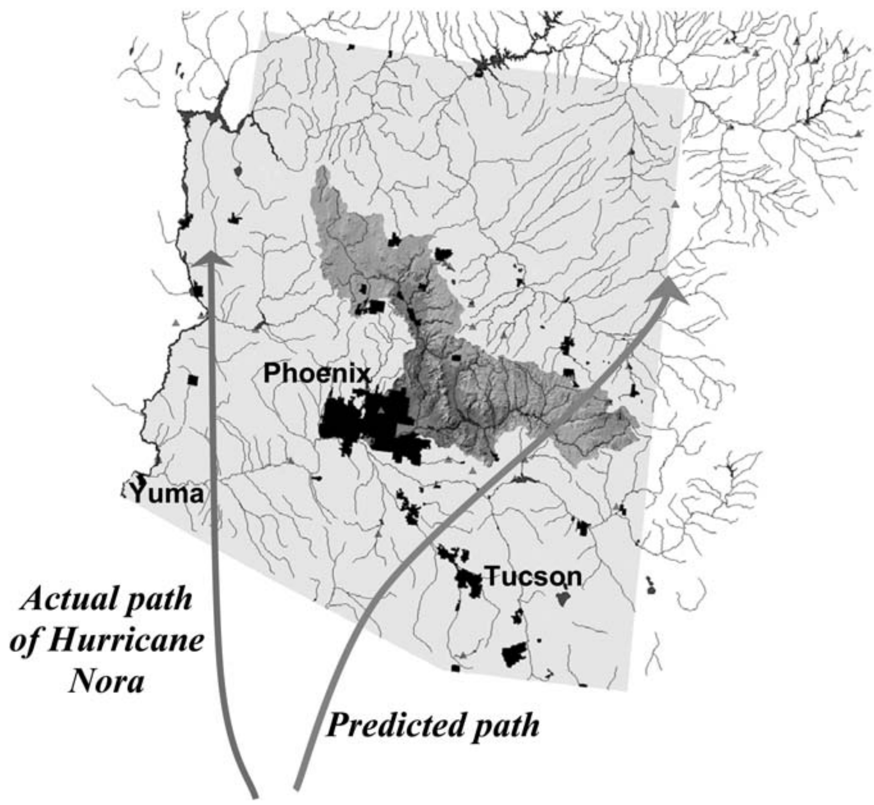

Figure 6. Implications of short-term prediction accuracy, illustrated by the predicted and actual paths of Hurricane Nora.

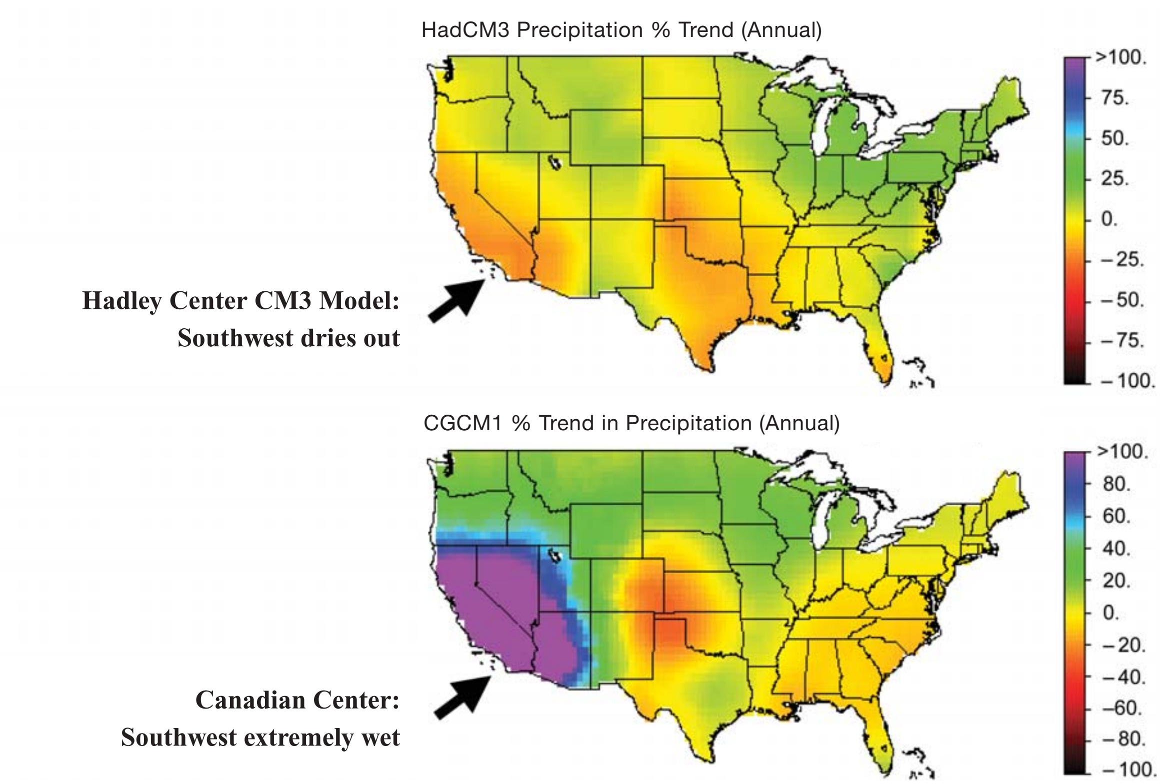

Figure 7. U.S. national assessment of climate model prediction accuracy: two different models make critically different predictions.

operators of the Roosevelt reservoir followed their usual operating guidelines and did not release any major amount of water in anticipation of the incoming storm's runoff. In this case, their decision was adequate, given that the storm runoff did not materialize. The point of the above example is that water resources managers will require reliable information both in long- and short-term time scales in order to operate their systems in a responsible manner. At this time, climate predictions are not reliable enough for water resources managers to feel comfortable deviating from standard operating policies.

The issue of climate prediction reliability is even more critical for long-term water resources planning purposes (decade to century time scales). For instance, the design of a new reservoir system requires planning for its physical lifespan to last on the order of a hundred years. Therefore, climatic trends at centennial time scales toward wetter or drier conditions will have a profound impact on optimal sizing of the structure. However, the state-of-the-art of climate modeling falls short of providing adequate information that can be utilized at regional scales. Figure 7 was reported in the US Global Change Research Program study related to a National Assessment of the climate change impacts on the United States (National Assessment Synthesis Team, 2000). Two climate models show vastly different predictions for the 21st Century, especially for the eastern two-thirds of the United States. The Canadian model projects a decrease in precipitation except for the Great Lakes and Northern Plains, while the Hadley model predicts continued precipitation increases in most areas. Certainly with improvements in the ability of climate models to provide more consistent predictions, the likelihood that the information will be utilized by the water resources community will increase.

Another example is shown in Figure 8, where two Hadley Center models – one older and one updated – are compared for their climate predictions. In the older model, a wetter climate is predicted for a large portion of the Northwest US and northeast of South America. In the updated model, however, the results plot at the opposite end of the scale: a remarkably drier climate is predicted for these same regions. Discrepancies such as these are not uncommon among global climate models (GCMs).

It is evident from these examples that water managers need a clearer understanding of how water resources issues vary in both time and space, as well as an understanding of how the quality of hydrological predictions varies spatially and temporally, as outlined previously in Figure 5. The ultimate goal of GCMs is to produce reliable results not only at the global scale, and for decadal and century-length predictions, but also for smaller basins and watersheds, and for shorter-term predictions.

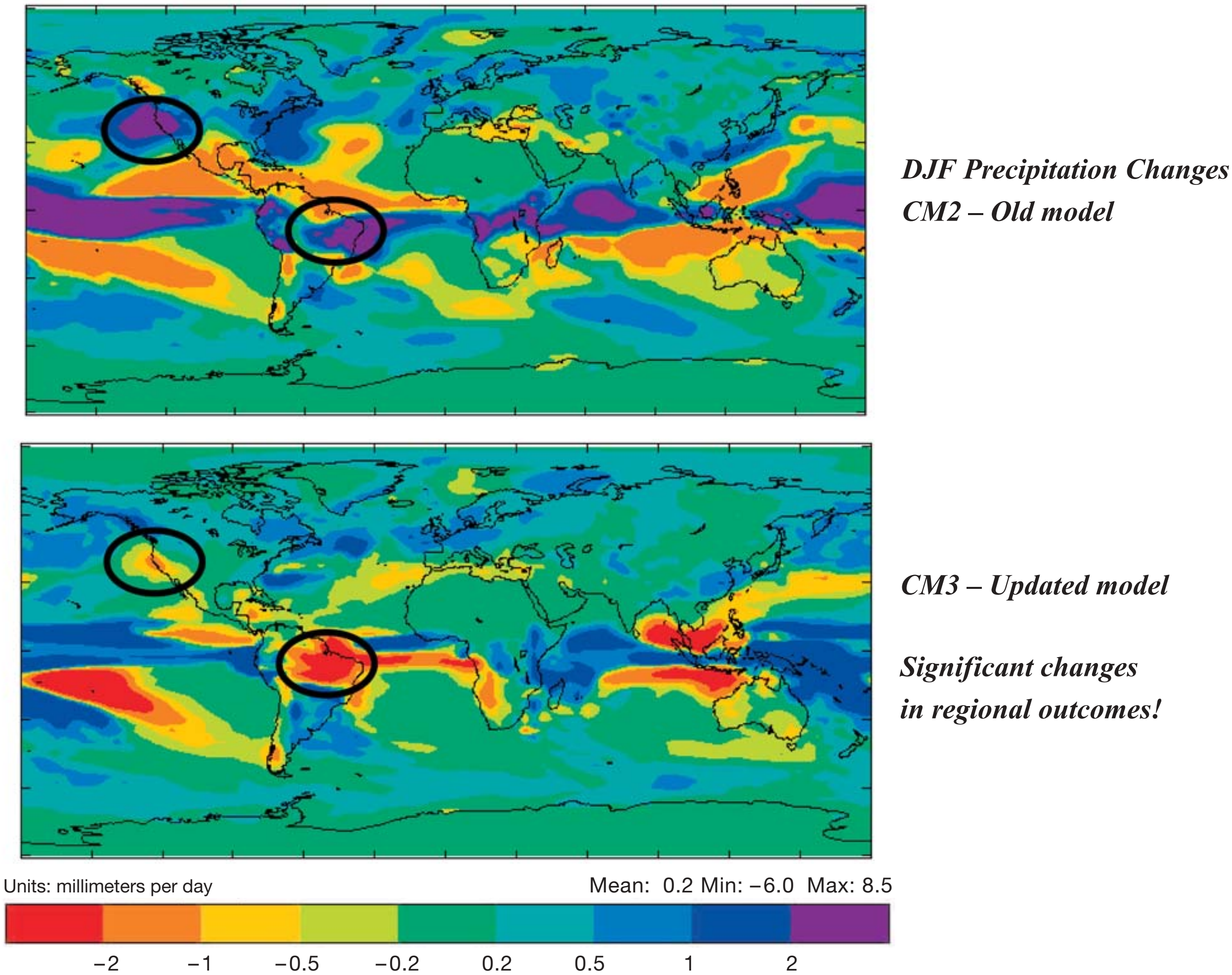

Figure 8. Hadley Center climate change projections for an older and updated model. Results show significant differences in regional outcomes.

The role of GEWEX in water cycle studies

To improve the accuracy of various global and mesoscale climate models with potential application to hydrologic predictions, the role of land-surface feedback cannot be ignored. To study and improve our understanding of this role requires well-coordinated, long-term monitoring, process studies, and modeling. The World Climate Research Programme's Global Energy and Water cycle EXperiment, "WCRP-GEWEX", was intended to provide this capability (Global Energy and Water cycle EXperiment, 2002a). GEWEX is a collaboration of international research programmes whose objectives are to observe and model the hydrologic cycle and energy fluxes in the atmosphere, and at the land and ocean surfaces.

Phase I of GEWEX, which covered the last decade, focused on four primary objectives: 1) Determine the hydrological cycle and energy fluxes by means of global measurements of observable atmospheric and surface properties; 2) model the global hydrological cycle and its impact on the atmosphere, oceans, and on the land surface; 3) develop the ability to predict the variations of global and regional hydrological processes and water resources, and their response to environmental change; and 4) foster the development of observing techniques, data management, and assimilation systems suitable for operational applications to long-range weather forecasts, hydrology, and climate predictions.

An essential step toward meeting these objectives is comparing model formulations of hydrological and energetic processes with corresponding observed properties. Accordingly, during GEWEX Phase I, several continental-scale experiments (CSEs) were established to create data sets of hydrometeorologic variables within continental-scale basins in a variety of climatic regions (Global Energy and Water Cycle Experiment, 2002a, 2002b). These CSEs will not only provide improved observations, but will also improve coupled land-atmosphere models. Some of these experiments, such as the GEWEX Continental-scale International Project (GCIP), have reached maturity and are being followed by extensions such as the GEWEX Americas Prediction Project (GAPP), which focuses more on seasonal time scales. Moreover, GAPP has extended its geographic coverage to include the southwestern and western US, where the hydrometeorology is complicated by a number of factors (e.g., topography).

GEWEX is currently entering Phase II, which, in the context of the original objectives, will address the following principal scientific questions: 1) Are the Earth's energy budget and water cycle changing? 2) How do processes contribute to feedback and causes of natural variability? 3) Can we predict these changes up to seasonal and interannual time scales? 4) What are the impacts of these changes on water resources? One of the primary elements of Phase II is the Coordinated Enhanced Observing period (CEOP), which was initiated in 2001. CEOP is geared toward bringing together in situ, satellite, and model data (with global coverage over the same time period) to support key science objectives in climate prediction and monsoon system studies (CEOP, 2002). Also in Phase II of GEWEX, there will be increasing interaction with the water resources and applications communities to ensure the usefulness of GEWEX results. This will require the development and use of a wide range of modeling tools ranging from the full global climate models, to regional and mesoscale models, and downscaling methods suitable for the smaller spatial and temporal scales generally associated with hydrological models used in local water resource management.

It is interesting to note that, internationally, the issues related to the understanding of the water cycle are receiving increased priority. For instance, in the United States, there is a concerted effort through a multi-agency initiative to secure research funding through congressional initiatives. One of the central elements of the water cycle initiative will be better spatial and temporal monitoring of precipitation from space satellites. In addition to hydrologists, many climate modelers assert that improvement of global precipitation measurements is a primary means by which to improve global climate model (GCM) output. In fact, the US has plans to launch the global precipitation mission (GPM) by the end of this decade, with the objective of providing high spatial resolution precipitation estimates at three-hour intervals across the entire planet.

The Global Precipitation Measurement mission (GPM), expected to begin around 2006, is a follow-up to the Tropical Rainfall Measuring Mission (TRMM). TRMM is an Earth-observation satellite program that supports: the expansion of observational areas (from the tropical to the global area); the improvement of observing frequency (drafting a global precipitation map every three hours); and the enhancement of measuring methods (identifying rain and snow using the dual-frequency precipitation radar (DPR) and improving a rainfall estimation) (Global Precipitation Measurement mission, 2002). Unlike TRMM, which primarily samples the tropics, GPM will sample both the tropics and mid-latitudes. The data are expected to have substantial impact upon quantitative precipitation estimation/forecasting and data assimilation into global and mesoscale numerical models. The data will also be useful for monitoring and predicting meteorological changes, including global warming in the long term, and for responding to social needs such as weather forecasts, and water resource management in the short term. Based upon previous studies of rainfall data assimilation, GPM is expected to lead to significant improvements in forecasts of extratropical and tropical cyclones. For example, GPM rainfall data can provide improved initialization of frontal systems over the Pacific and Atlantic Oceans (Global Precipitation Measurement mission, 2002).

Strategies for improved precipitation estimation

In addition to the more traditional methods of precipitation estimation, several satellite systems now offer multiple sources of precipitation estimates and related measurements. Such satellites include NASA EOS (MODIS, IR+VIS), NASA TRMM (TMI, PR, VIRS), and GOES (IR VIS SOUNDING). Combined with ground measurements using radar, traditional rain gages, and in situ data collection of surface temperature, soil moisture, vegetation, topography (elevation and slope), as well as wind speed and direction, these satellite measurements offer substantial data sets to powerfully improve the accuracy of GCM output.

PERSIANN (Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks) is a system that uses multiple sources of information in global precipitation estimation (Sorooshian et al., 2000). Specifically, the PERSIANN system extracts cloud-top temperature and texture information from geosynchronous satellite infrared images to estimate surface rainfall rates from an artificial neural network system. Other sources of information – from polar orbiting satellites (TRMM and DMSP) and ground-based observations (radar and gauges) – are used to update the parameters of the PERSIANN system. The PERSIANN rainfall estimates are generated every 30 minutes, 0.25 × 0.25 latitude/longitude resolution, and are accumulated at various spatial-temporal scales, such as 6-hour, daily, and monthly periods. Rain estimates are available through HyDIS (Hydrologic Data and Information System) hydis.hwr.arizona.edu at The University of Arizona. Figure 9 shows the six-hour accumulated rainfall from radar observation, PERSIANN estimates, and RAMS (RAdiation Measurement System) estimates. Over the southwest US region, rainfall observations from radar are

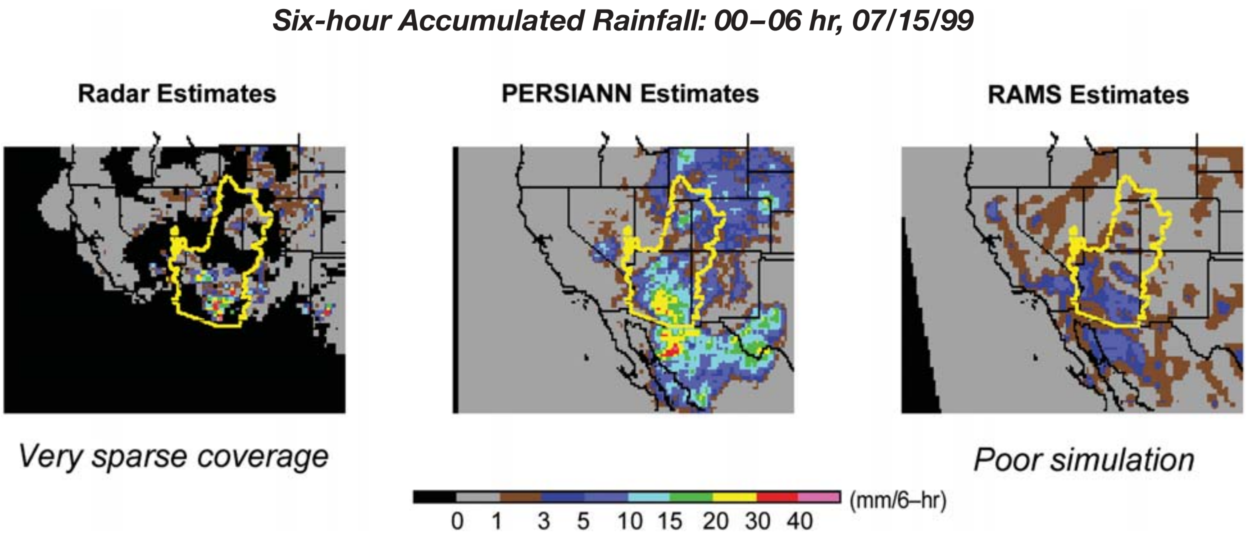

Figure 9. PERSIANN vs RAMS precipitation estimates.

very limited because radar beams are blocked by mountains. As shown in the figure, the PERSIANN system of using multiple sources of information provides good rainfall estimates covering the full southwest US region and upper Mexico. The rainfall estimates from the numerical weather prediction model (RAMS), however, underestimate the accumulated rainfall from the model simulation.

In addition to improvements in rainfall estimation, the mapping of snowpack is an important ongoing data processing task because most runoff and recharge comes from snowmelt. Serreze et al. (1999) reported that for several western and southwestern US regions, a large percentage of annual precipitation can be attributed to snow. For example, the Salt-Verde watershed supplies water to the Phoenix, Arizona metropolitan area. The amount of seasonal snowfall and subsequent runoff/recharge directly affects the available water supply. Providing water resource managers and policy makers with reliable estimates of recharge from snowmelt would vastly facilitate decisions pertaining to water allocation. Figure 10 shows that winter precipitation in the Salt River basin can vary drastically each year. Recharge from the 1993 snowmelt resulted in an estimated 2.25-year supply of water, but the year 2000 was considerably drier during the winter months, and the subsequent snowmelt resulted in only a 3-month supply of water.

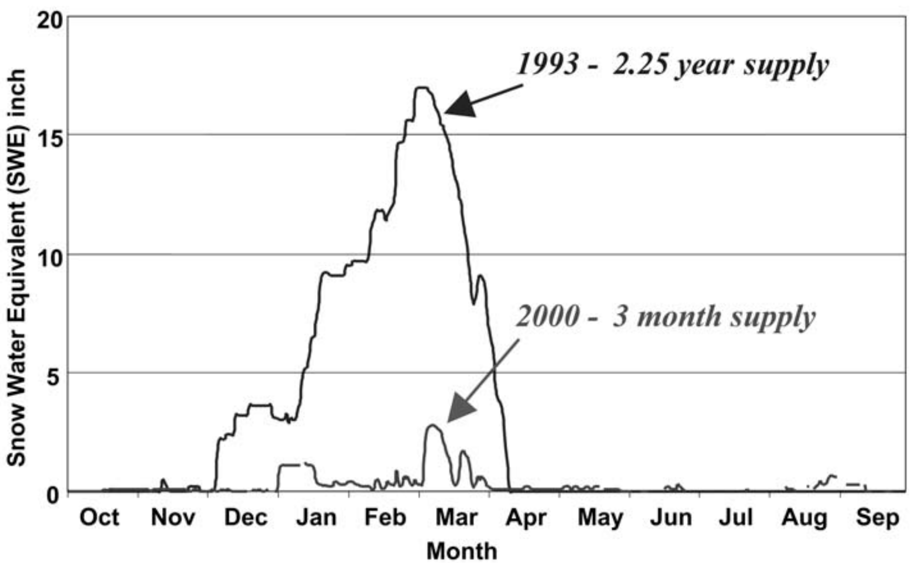

Figure 10. The Phoenix, Arizona water supply is drastically affected by winter precipitation and the subsequent springtime recharge of snowmelt from local mountain watersheds.

Springtime runoff and recharge is thus largely affected by snowmelt. One possible improvement of climate models may occur with improved snow mapping. The application of climate model predictions for smaller temporal and spatial scales would be very useful in the context of correlating snow mapping with temporal estimates of springtime snowmelt and subsequent runoff and recharge volumes. As demonstrated by the Phoenix, Arizona example, it is critical to understand the various hydrological aspects of arid and semiarid regions. In the next section, we discuss the importance of exploring hydrological research in semiarid regions, and outline the role of a newly-founded semiarid hydrology research center.

Hydrologic issues of semiarid regions: The role of SAHRA

The water resources issues of arid and semiarid regions of the world, where populations grow more rapidly than the global average, is likely to create new challenges for many nations located in dry climatic zones. Arid and semiarid regions cover one-third of Earth's continental landmasses. Moreover, these regions typically receive less than 400 mm of precipitation annually (WRRC, 1999), yet the evapotranspiration (ET) rates are especially large, thus leaving a small percentage of total precipitation available for snowpack and subsequent recharge. Superimposing the uncertainty of climate change and variability in the heavily populated and water-scarce, semiarid regions demands close examination by the scientific community. These areas are likely to show the greatest sensitivity to climate change, with great social and economic consequences. Recognizing the importance of these issues, particularly in the context of the semiarid US, the US National Science Foundation is supporting a Science and Technology Center, SAHRA (Sustainability of semi-Arid Hydrology and Riparian Areas). While the long-term goal geographical domain of SAHRA is any area that is arid or semiarid, the initial, current focus is specifically centered on several US basins as case studies that may later be linked, shared, and "exported" to other areas. In this context, five specific science areas are being pursued by SAHRA, as follows:

1. *Spatial and temporal components of the water balance*. This involves estimating and modeling snow accumulation, distribution, and melt; evapotranspiration/sublimation; runoff; and infiltration. Approaches include intensive and continuous field observations, coupled with modeling, in subalpine areas and a variety of ecological locations on the desert floor.
2. *Basin-scale water and solute balances*. The major goal is to understand the dynamics of water and solute balances in semi-arid regions at large spatial and temporal scales (i.e., the river basin scale and decadal and longer time scales). Recharge mechanisms in basin floors and ephemeral channels, impacts of vegetative cover, and sources and sinks of salt are being studied.
3. *Functioning of riparian ecosystems*. Research in this area is aimed at understanding how riparian systems affect, and are affected by, changes in water quantity (e.g., due to ground-water pumping or conjunctive stream water management) or water quality (i.e., nitrogen inputs from precipitation or agricultural runoff). Current research approaches are quantifying and modeling fluxes of water, energy, and nutrients.
4. *Water as a resource: competition, conflict, planning, and policy*. Researchers in this area are examining issues related to water resources policy, including behavioral, sociological, and economic factors, in semi-arid regions of the southwestern United States. Experimental economic research, collection of field survey data, and innovative approaches to disaggregating domestic water uses are being used to analyze shifting drivers of water demand and conservation opportunities, nonmarket water uses, and water resource management and operations.
5. *Multi-resolution integrated modeling of basin-scale processes*. Tools such as supercomputer-based virtual watersheds and dynamic simulation models are integrating emerging scientific understanding into comprehensive river-basin models which can be used in the analysis of water resources management issues.

A detailed description of SAHRA's research agenda and specific projects, in addition to some results of the first two years of research, are found on SAHRA's web site (SAHRA, 2002).

Conclusions

The above discussion has provided an overview of some of the critical hydrology and water resources issues facing us in the forthcoming decades. We have described some of the ongoing programs and research activities geared toward improving our understanding of the elements of the global and regional water cycles. Naturally, the system as a whole is extremely complex and nonlinear, and it therefore requires a combination of observational process studies and modeling. It is important to note that it is not only the better understanding of the physical aspects of hydrology that is required to address future water resources (both quantity and quality) of various nations of the world; social and economic aspects must also be considered. It is no wonder that many research groups are forming interdisciplinary partnerships to take an end-to-end approach to the study of hydrology and water resources.

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